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System Protection

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Miroslav Begovic

Georgia Institute of Technology

4.1 Introduction

While most of the protective system designs are made around individual components, system-wide disturbances in power systems are becoming a frequent and challenging problem for the electric utilities. The occurrence of major disturbances in power systems requires coordinated protection and control actions to stop the system degradation, restore the normal state, and minimize the impact of the disturbance. Local protection systems are often not capable of protecting the overall system, which may be affected by the disturbance. Among the phenomena, which create the power system, disturbances are various types of system instability, overloads, and power system cascading [1–5].

The power system planning has to account for tight operating margins, with less redundancy, because of new constraints placed by restructuring of the entire industry. The advanced measurement and communication technology in wide area monitoring and control are expected to provide new, faster, and better ways to detect and control an emergency [6].

4.2 Disturbances: Causes and Remedial Measures [7]

Phenomena that create power system disturbances are divided, among others, into the following categories: transient instabilities, voltage instabilities, overloads, power system cascading, etc. They are mitigated using a variety of protective relaying and emergency control measures.

Out-of-step protection has the objective to eliminate the possibility of damage to generators as a result of an out-of-step condition. In case the power system separation is imminent, it should separate the system along the boundaries, which will form islands with balanced load and generation. Distance relays are often used to provide an out-of-step protection function, whereby they are called upon to provide blocking or tripping signals upon detecting an out-of-step condition.

The most common predictive scheme to combat loss of synchronism is the equal-area criterion and its variations. This method assumes that the power system behaves like an equivalent two-machine model

where one area oscillates against the rest of the system. Whenever the underlying assumption holds true, the method has potential for fast detection.

Voltage instabilities in power systems arise from heavy loading, inadequate reactive support resources, unforeseen contingencies and/or mis-coordinated action of the tap-changing transformers. Such incidents can lead to system-wide blackouts (which have occurred in the past and have been documented in many power systems world-wide).

The risk of voltage instability increases as the transmission system becomes more heavily loaded. The typical scenario of these instabilities starts with a high system loading, followed by a relay action due to a fault, a line overload, or operation beyond an excitation limit.

Overload of one, or a few power system elements may lead to a cascading overload of many more elements, mostly transmission lines, and ultimately, it may lead to a complete power system blackout.

A quick, simple, and reliable way to reestablish active power balance is to shed load by underfrequency relays. There are a large variety of practices in designing load shedding schemes based on the characteristics of a particular system and the utility practices.

While the system frequency is a consequence of the power deficiency, the rate of change of frequency is an instantaneous indicator of power deficiency and can enable incipient recognition of the power imbalance. However, change of the machine speed is oscillatory by nature, due to the interaction among the generators. These oscillations depend on location of the sensors in the island and the response of the generators. A system having smaller inertia causes a larger peak-to-peak value for oscillations, requiring enough time for the relay to calculate the actual rate of change of frequency reliably. Measurements at load buses close to the electrical center of the system are less susceptible to oscillations (smaller peak-to-peak values) and can be used in practical applications. A system having smaller inertia causes a higher frequency of oscillations, which enables faster calculation of the actual rate of change of frequency. However, it causes faster rate of change of frequency and consequently, a larger frequency drop. Adaptive settings of frequency and frequency derivative relays may enable implementation of a frequency derivative function more effectively and reliably.

4.3 Transient Stability and Out-of-Step Protection

Every time when a fault or a topological change affects the power balance in the system, the instantaneous power imbalance creates oscillations between the machines. Stable oscillations lead to transition from one (prefault) to another (postfault) equilibrium point, whereas unstable ones allow machines to oscillate beyond the acceptable range. If the oscillations are large, then the stations' auxiliary supplies may undergo severe voltage fluctuations, and eventually trip [1]. Should that happen, the subsequent resynchronization of the machines might take a long time. It is, therefore, desirable to trip the machine exposed to transient unstable oscillations while preserving the plant auxiliaries energized.

The frequency of the transient oscillations is usually between 0.5 and 2 Hz. Since the fault imposes almost instantaneous changes on the system, the slow speed of the transient disturbances can be used to distinguish between the two. For the sake of illustration, let us assume that a power system consists of two machines, A and B, connected by a transmission line. [Figure 4.1](#) represents the trajectories of the stable and unstable swings between the machines, as well as a characteristic of the mho relay covering the line between them, shown in the impedance plane. The stable swing moves from the distant stable operating point toward the trip zone of the relay, and may even encroach it, then leave again. The unstable trajectory may pass through the entire trip zone of the relay. The relaying tasks are to detect, and then trip (or block) the relay, depending on the situation. Detection is accomplished by out-of-step relays, which have multiple characteristics. When the trajectory of the impedance seen by the relays enters the outer zone (a circle with a larger radius), the timer is activated, and depending on the speed at which the impedance trajectory moves into the inner zone (a circle with a smaller radius), or leaves the outer zone, a tripping (or blocking) decision can be made. The relay characteristic may be chosen to be straight lines, known as “blindings,” which prevent the heavy load to be misrepresented as a fault, or

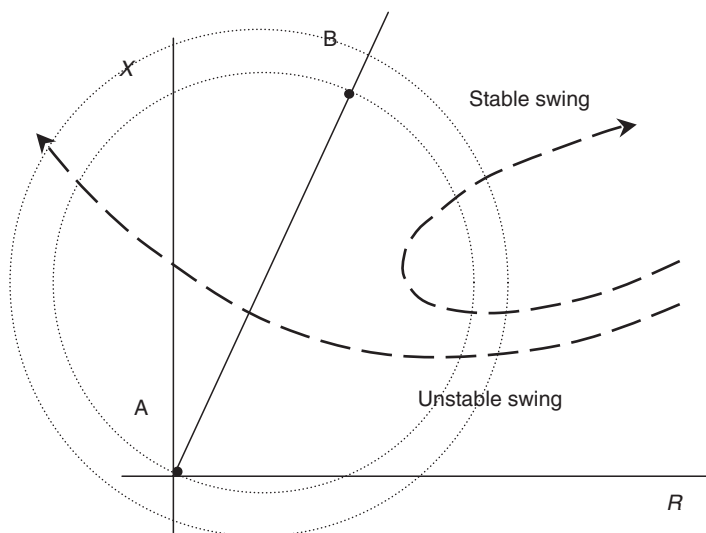


FIGURE 4.1 Trajectories of stable and unstable swings in the impedance plane.

instability. Another information that can be used in detection of transient swings is that they are symmetrical, and do not create any zero, or negative sequence currents.

In the case when power system separation is imminent, out-of-step protection should take place along boundaries, which will form islands with matching load and generation. Distance relays are often used to provide an out-of-step protection function, whereby they are called upon to provide blocking or tripping signals upon detecting an out-of-step condition. The most common predictive scheme to combat loss of synchronism is the equal-area criterion and its variations. This method assumes that the power system behaves like a two-machine model where one area oscillates against the rest of the system. Whenever the underlying assumption holds true, the method has potential for fast detection.

4.4 Overload and Underfrequency Load Shedding

Outage of one or more power system components due to the overload may result in overload of other elements in the system. If the overload is not alleviated in time, the process of power system cascading may start, leading to power system separation. When a power system separates, islands with an imbalance between generation and load are formed. One consequence of the imbalance is deviation of frequency from the nominal value. If the generators cannot handle the imbalance, load or generation shedding is necessary. A special protection system or out-of-step relaying can also start the separation.

A quick, simple, and reliable way to reestablish active power balance is to shed load by underfrequency relays. The load shedding is often designed as a multistep action, and the frequency settings and blocks of load to be shed are carefully selected to maximize the reliability and dependability of the action. There are a large variety of practices in designing load shedding schemes based on the characteristics of a particular system and the utility practices. While the system frequency is a final result of the power deficiency, the rate of change of frequency is an instantaneous indicator of power deficiency and can enable incipient recognition of the power imbalance. However, change of the machine speed is oscillatory by nature, due to the interaction among generators. These oscillations depend on location of the sensors in the island and the response of the generators. The problems regarding the rate of change of frequency function are:

- Systems having small inertia may cause larger oscillations. Thus, enough time must be allowed for the relay to calculate the actual rate of change of frequency reliably. Measurements at load buses close to the electrical center of the system are less susceptible to oscillations (smaller peak-to-peak

values) and can be used in practical applications. Smaller system inertia causes a higher frequency of oscillations, which enables faster calculation of the actual rate of change of frequency. However, it causes a faster rate of change of frequency and consequently, a larger frequency drop.

- Even if rate of change of frequency relays measure the average value throughout the network, it is difficult to set them properly, unless typical system boundaries and imbalance can be predicted. If this is the case (e.g., industrial and urban systems), the rate of change of frequency relays may improve a load shedding scheme (scheme can be more selective and/or faster).

4.5 Voltage Stability and Undervoltage Load Shedding

Voltage stability is defined by the “System Dynamic Performance Subcommittee of the IEEE Power System Engineering Committee” as being the ability of a system to maintain voltage such that when load admittance is increased, load power will increase, so that both power and voltage are controllable. Also, voltage collapse is defined as being the process by which voltage instability leads to a very low voltage profile in a significant part of the system. It is accepted that this instability is caused by the load characteristics, as opposed to the angular instability, which is caused by the rotor dynamics of generators.

Voltage stability problems are manifested by several distinguishing features: low system voltage profiles, heavy reactive line flows, inadequate reactive support, and heavily loaded power systems. The voltage collapse typically occurs abruptly, after a symptomatic period that may last in the time frames of a few seconds to several minutes, sometimes hours. The onset of voltage collapse is often precipitated by low-probability single or multiple contingencies. The consequences of collapse often require long system restoration, while large groups of customers are left without supply for extended periods of time. Schemes which mitigate against collapse need to use the symptoms to diagnose the approach of the collapse in time to initiate corrective action.

Analysis of voltage collapse models can be divided into two main categories, static or dynamic:

- Fast: disturbances of the system structure, which may involve equipment outages, or faults followed by equipment outages. These disturbances may be similar to those which are consistent with transient stability symptoms, and sometimes the distinction is hard to make, but the mitigation tools for both types are essentially similar, making it less important to distinguish between them.
- Slow: load disturbances, such as fluctuations of the system load. Slow load fluctuations may be treated as inherently static. They cause the stable equilibrium of the system to move slowly, which makes it possible to approximate voltage profile changes by a discrete sequence of steady states rather than a dynamic model.

Figure 4.2 shows a symbolic depiction of the process of coalescing of the stable and unstable power system equilibria (saddle node bifurcation) through slow load variations, which leads to a voltage collapse (a precipitous departure of the system state along the center manifold at the moment of coalescing). VPQ curve (see Fig. 4.2) represents the trajectory of the load voltage V of a two-bus system model when active (P) and reactive (Q) powers of the load can change arbitrarily.

Figure 4.2 represents a trajectory of the load voltage V when active (P) and reactive (Q) powers change independently. It also shows the active and reactive power margins as projections of the distances. The voltage stability boundary is represented by a projection onto the PQ plane (a bold curve). It can be observed that: (a) there may be many possible trajectories to (and points of) voltage collapse; (b) active and reactive power margins depend on the initial operating point and the trajectory to collapse.

There have been numerous attempts to use the observations and find accurate voltage collapse proximity indicators. They are usually based on measurement of the state of a given system under stress and derivation of certain parameters which indicate the stability or proximity to instability of that system.

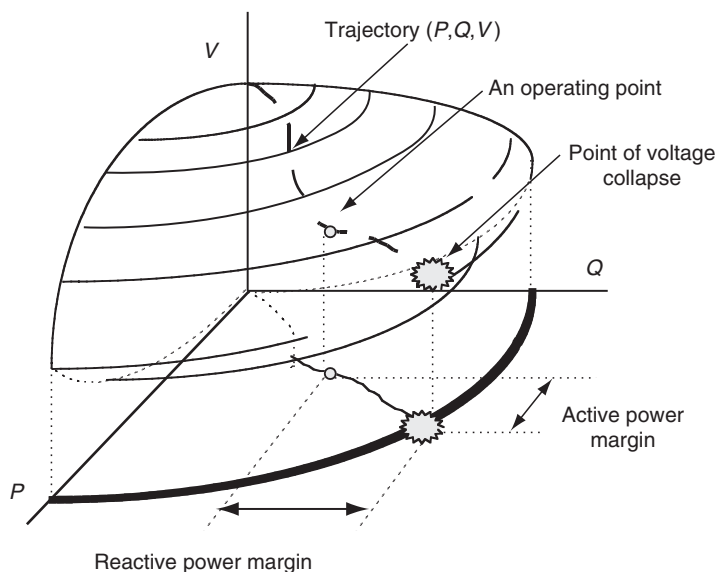


FIGURE 4.2 Relationship between voltages, active and reactive powers of the load and voltage collapse.

Parameters based on measurement of system condition are useful for planning and operating purposes to avoid the situation where a collapse might occur. However, it is difficult to calculate the system condition and derive the parameters in real time. Rapid derivation and analysis of these parameters are important to initiate automatic corrective actions fast enough to avoid collapse under emergency conditions, which arise due to topological changes or very fast load changes.

It is preferable if a few critical parameters that can be directly measured could be used in real time to quickly indicate proximity to collapse. An example of such indicator is the sensitivity of the generated reactive powers with respect to the load parameters (active and reactive powers of the loads). When the system is close to a collapse, small increases in load result in relatively large increases in reactive power absorption in the system. These increases in reactive power absorption must be supplied by dynamic sources of reactive power in the region. At the point of collapse, the rate of change of generated reactive power at key sources with respect to load increases at key busses tends to infinity.

The sensitivity matrix of the generated reactive powers with respect to loading parameters is relatively easy to calculate in off-line studies, but could be a problem in real-time applications, because of the need for system-wide measurement information. Large sensitivity factors reveal both critical generators (those required to supply most of the newly needed reactive power) and critical loads (those whose location in the system topology imposes the largest increase in reactive transmission losses, even for the modest changes of their own load parameters). The norm of such a sensitivity matrix represents a useful proximity indicator, but one that is still relatively difficult to interpret. It is not the generated reactive power, but its derivatives with respect to loading parameters which become infinite at the point of imminent collapse.

Voltage instability can be alleviated by a combination of the following remedial measures: adding reactive compensation near load centers, strengthening the transmission lines, varying the operating conditions such as voltage profile and generation dispatch, coordinating relays and controls, and load shedding. Most utilities rely on planning and operation studies to guard against voltage instability. Many utilities utilize localized voltage measurements in order to achieve load shedding as a measure against incipient voltage instability. The efficiency of the load shedding depends on the selected voltage thresholds, locations of pilot points in which the voltages are monitored, locations and sizes of the blocks of load to be shed, as well as the operating conditions, which may activate the shedding. The wide variety of conditions that may lead to voltage instability suggests that the most accurate decisions should imply the adaptive relay settings, but such applications are still in the stage of early development.

4.6 Special Protection Schemes

Increasingly popular over the past several years are the so-called special protection systems, sometimes also referred to as remedial action schemes [8,9]. Depending on the power system in question, it is sometimes possible to identify the contingencies, or combinations of operating conditions, which may lead to transients with extremely disastrous consequences [10]. Such problems include, but are not limited to, transmission line faults, the outages of lines and possible cascading that such an initial contingency may cause, outages of the generators, rapid changes of the load level, problems with high voltage DC (HVDC) transmission or flexible AC transmission systems (FACTS) equipment, or any combination of those events.

Among the many varieties of special protection schemes (SPS), several names have been used to describe the general category [2]: special stability controls, dynamic security controls, contingency arming schemes, remedial action schemes, adaptive protection schemes, corrective action schemes, security enhancement schemes, etc. In the strict sense of protective relaying, we do not consider any control schemes to be SPS, but only those protective relaying systems, which possess the following properties [9]:

- SPS can be operational (armed), or out of service (disarmed), in conjunction with the system conditions.
- SPS are responding to very low-probability events; hence they are active rarely more than once a year.
- SPS operate on simple, predetermined control laws, often calculated based on extensive off-line studies.
- Often times, SPS involve communication of remotely acquired measurement data (supervisory control and data acquisition [SCADA]) from more than one location in order to make a decision and invoke a control law.

The SPS design procedure is based on the following [2]:

- *Identification of critical conditions:* On the grounds of extensive off-line steady state studies on the system under consideration, a variety of operating conditions and contingencies are identified as potentially dangerous, and those among them which are deemed the most harmful are recognized as the critical conditions. The issue of their continuous monitoring, detection, and mitigation is resolved through off-line studies.
- *Recognition triggers:* Those are the measurable signals that can be used for detection of critical conditions. Often times, such detection is accomplished through a complicated heuristic logical reasoning, using the logic circuits to accomplish the task: “If event A and event B occur together, or event C occurs, then...” inputs for the decision making logic are called recognition triggers, and can be status of various relays in the system, sometimes combined with a number of (SCADA) measurements.
- *Operator control:* In spite of extensive simulations and studies done in the process of SPS design, it is often necessary to include the human intervention, i.e., to include human interaction in the feedback loop. This is necessary because SPS are not needed all the time, and the decision to arm or disarm them remains in the hands of an operator.

Among the SPS reported in the literature [8,9], the following schemes are represented:

- Generator rejection
- Load rejection
- Underfrequency load shedding
- System separation
- Turbine valve control
- Stabilizers
- HVDC controls

- Out-of-step relaying
- Dynamic braking
- Generator runback
- VAR compensation
- Combination of schemes

Some of them have already been described in the above text. A general trend continues toward more complex schemes, capable of outperforming the present solutions, and taking advantage of the most recent technological developments, and advances in systems analysis. Some of the trends are described in the following text [6].

4.7 Modern Perspective: Technology Infrastructure

4.7.1 Phasor Measurement Technology [7]

The technology of synchronized phasor measurements is well established, and is rapidly gaining acceptance as a platform for monitoring systems. It provides an ideal measurement system with which to monitor and control a power system, in particular during stressed conditions. The essential feature of the technique is that it measures positive sequence voltages and currents of a power system in real time with precise time synchronization. This allows accurate comparison of measurements over widely separated locations as well as potential real-time measurement based control actions. Very fast recursive discrete fourier transform (DFT) calculations are normally used in phasor calculations.

The synchronization is achieved through a global positioning satellite (GPS) system. GPS is a U.S. Government sponsored program that provides world-wide position and time broadcasts free of charge. It can provide continuous precise timing at better than the 1 μ s level. It is possible to use other synchronization signals, if these become available in the future, provided that a sufficient accuracy of synchronization could be maintained. Local, proprietary systems can be used such as a sync signal broadcast over microwave or fiber optics. Two other precise positioning systems, global navigation satellite system (GLONASS), a Russian system, and Galileo, a proposed European system, are also capable of providing precise time. The GPS transmission is obtained by the receiver, which delivers a phase-locked sampling clock pulse to the analog-to-digital converter system. The sampled data are converted to a complex number which represents the time-tagged phasor of the sampled waveform. Phasors of all three phases are combined to produce the positive sequence measurement.

Any computer-based relay which uses sampled data is capable of developing the positive sequence measurement. By using an externally derived synchronizing pulse, such as from a GPS receiver, the measurement could be placed on a common time reference. Thus, potentially all computer-based relays could furnish the synchronized phasor measurement. When currents are measured in this fashion, it is important to have a high enough resolution in the analog-to-digital converter to achieve sufficient accuracy of representation at light loads. A 16 bit A/D converter generally provides adequate resolution to read light load currents, as well as fault currents.

For the most effective use of phasor measurements, some kind of a data concentrator is required. The simplest is a system that will retrieve files recorded at the measurement site and then correlate files from different sites by the recording time stamps. This allows doing system and event analysis utilizing the precision of phasor measurement. For real-time applications, continuous data acquisition is required. Phasor concentrator inputs phasor measurement data broadcast from a large number of PMUs, and performs data checks, records disturbances, and rebroadcasts the combined data stream to other monitor and control applications. This type of unit fulfills the need for both hard and soft real-time applications as well as saving data for system analysis. Tests performed using this phasor monitoring unit–phasor data concentrator (PMU–PDC) technology have shown the time intervals from measurement to data availability at a central controller can be as fast as 60 ms for a direct

link and 200 ms for secondary links. These times meet the requirements for many types of wide area controls.

A broader effort is the wide area measurement system (WAMS) concept. It includes all types of measurements that can be useful for system analysis over the wide area of an interconnected system. Real-time performance is not required for this type of application, but is no disadvantage. The main elements are time tags with enough precision to unambiguously correlate data from multiple sources and the ability to all data to a common format. Accuracy and timely access to data are important as well. Certainly with its system-wide scope and precise time tags, phasor measurements are a prime candidate for WAMS.

4.7.2 Communication Technology [7]

Communications systems are a vital component of a wide area relay system. These systems distribute and manage the information needed for operation of the wide area relay and control system. However, because of potential loss of communication, the relay system must be designed to detect and tolerate failures in the communication system. It is important also that the relay and communication systems be independent and subject as little as possible to the same failure modes. This has been a serious source of problems in the past.

To meet these difficult requirements, the communications network needs to be designed for fast, robust, and reliable operation. Among the most important factors to consider in achieving these objectives are type and topology of the communications network, communications protocols, and media used. These factors will in turn effect communication system bandwidth, usually expressed in bits per second (BPS), latency in data transmission, reliability, and communication error handling.

Presently, electrical utilities use a combination of analog and digital communications systems for their operations consisting of power line carrier, radio, microwave, leased phone lines, satellite systems, and fiber optics. Each of these systems has applications, where it is the best solution. The advantages and disadvantages of each are briefly summarized in the following paragraph.

Power line carrier is generally rather inexpensive, but has limited distance of coverage and low bandwidth. It is best suited to station-to-station protection and communications to small stations that are hard to access otherwise. Company owned microwave is cost effective and reliable but requires substantial maintenance. It is good for general communications for all types of applications. Radio tends to be narrower band but is good for mobile applications or locations hard to access otherwise. Satellite systems likewise are effective for reaching hard to access locations, but not good where the long delay is a problem. They also tend to be expensive. Leased phone lines are very effective where a one solid link is needed at a site served by a standard carrier. They tend to be expensive in the long-term, so are usually not the best solution where many channels area required. Fiber optic systems are the newest option. They are expensive to install and provision, but are expected to be very cost effective. They have the advantage of using existing right-of-way and delivering communications directly between points of use. In addition they have the very high bandwidth needed for modern data communications.

Several types of communication protocols are used with optical systems. Two of the most common are synchronous optical networks (Sonet/SDH) and asynchronous transfer mode (ATM). Wideband Ethernet is also gaining popularity, but is not often used for backbone systems. Sonet systems are channel oriented, where each channel has a time slot whether it is needed or not. If there is no data for a particular channel at a particular time, the system just stuffs in a null packet. ATM by contrast puts data on the system as it arrives in private packets. Channels are reconstructed from packets as they come through. It is more efficient as there are no null packets sent, but has the overhead of prioritizing and sorting the packets. Each system has different system management options for coping with problems.

Synchronous optical networks are well established in electrical utilities throughout the world and are available under two similar standards: (a) Sonet (synchronous optical networks) is the American System under ANSI T1.105 and Bellcore GR standards; (b) synchronous digital hierarchy (SDH) under the international telecommunications union (ITU) standards.

Sonet and SDH networks are based on a ring topology. This topology is a bidirectional ring with each node capable of sending data in either direction; data can travel in either direction around the ring to connect any two nodes. If the ring is broken at any point, the nodes detect where the break is relative to the other nodes and automatically reverse transmission direction if necessary. A typical network, however, may consist of a mix of tree, ring, and mesh topologies rather than strictly rings with only the main backbone being rings.

Self-healing (or survivability) capability is a distinctive feature of Sonet/SDH networks made possible because it is a ring topology. This means that if communication between two nodes is lost, the traffic among them switches over to the protected path of the ring. This switching to the protected path is made as fast as 4 ms, perfectly acceptable to any wide area protection and control.

Communication protocols are an intrinsic part of modern digital communications. Most popular protocols found in the electrical utility environment and suitable for wide area relaying and control are the distributed network protocol (DNP), Modbus, IEC870-5, and utility communication architecture/manufacturing message specifications (UCA/MMS). Transmission control protocol/Internet protocol (TCP/IP), probably the most extensively used protocol and will undoubtedly find applications in wide area relaying.

Utility communication architecture/manufacturing message specifications (UCA/MMS) protocol is the result of an effort between utilities and vendors (coordinated by Electric Power Research Institute). It addresses all communication needs of an electric utility. Of particular interest is its “peer to peer” communications capability that allows any node to exchange real-time control signals with any other node in a wide area network. DNP and Modbus are also real-time type protocols suitable for relay applications. TCP on Ethernet lacks a real-time type requirement, but over a system with low traffic performs as well as the other protocols. Other slower speed protocols like Inter Control Center Protocol (ICCP) (America) or TASEII (Europe) handle higher level but slower applications like SCADA. Many other protocols are available but are not commonly used in the utility industry.

4.8 Future Improvements in Control and Protection

Existing protection/control systems may be improved and new protection/control systems may be developed to better adapt to prevailing system conditions during system-wide disturbance. While improvements in the existing systems are mostly achieved through advancement in local measurements and development of better algorithms, improvements in new systems are based on remote communications. However, even if communication links exist, conventional systems that utilize only local information may still need improvement since they are supposed to serve as fall back positions. The increased functions and communication ability in today's SCADA systems provide the opportunity for an intelligent and adaptive control, and protection system for system-wide disturbance. This in turn can make possible full utilization of the network, which will be less vulnerable to a major disturbance.

Out-of-step relays have to be fast and reliable. The present technology of out-of-step tripping or blocking distance relays is not capable of fully dealing with the control and protection requirements of power systems. Central to the development effort of an out-of-step protection system is the investigation of the multiarea out-of-step situation. The new generation of out-of-step relays has to utilize more measurements, both local and remote, and has to produce more outputs. The structure of the overall relaying system has to be distributed and coordinated through a central control. In order for the relaying system to manage complexity, most of the decisions have to be taken locally. The relay system is preferred to be adaptive, in order to cope with system changes. To deal with out-of-step prediction, it is necessary to start with a system-wide approach, find out what sets of information are crucial, how to process information with acceptable speed and accuracy.

The protection against voltage instability should also be addressed as a part of hierarchical structure. The sound approach for designing the new generation of voltage instability protection is to first design a voltage instability relay with only local signals. The limitations of local signals should be identified in order to be in a position to select appropriate communicated signals. However, a minimum set of

communicated signals should always be known in order to design a reliable protection, and it requires the following: (a) determining the algorithm for gradual reduction of the number of necessary measurement sites with minimum loss of information necessary for voltage stability monitoring, analysis, and control; (b) development of methods (i.e., sensitivity analysis), which should operate *concurrent* with any existing local protection techniques, and possessing superior performance, both in terms of security and dependability.

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